Two-Stage Chirped-Beam SASE-FEL for High Power Femtosecond X-Ray Pulse Generation

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Disadvantages of standard SASE FEL configuration:

- Shot-to-shot fluctuations of radiation power after monochromator will increase with increasing photon energy resolution.

- Conventional x-ray optical elements (monochromator) may suffer damage due to the high output radiation power.

- Large shot-to-shot fluctuations in mean electron beam energy (0.1%) results in shot-to-shot fluctuations of resonant radiation frequency.

LCLS output radiation parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation wavelength</td>
<td>1.5 Å</td>
</tr>
<tr>
<td>Mean peak power</td>
<td>7.7 GW</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>2 \times 10^{-4}</td>
</tr>
<tr>
<td>Intensity fluctuations</td>
<td>6 %</td>
</tr>
<tr>
<td>Pulse duration, rms</td>
<td>67 fs</td>
</tr>
</tbody>
</table>

Schematic of SASE X-ray FEL:
Two-stage chirped pulse seeding for short pulse production:

Resonant condition: \( \omega = \frac{2 \omega_{\mu}}{\gamma^2} \gamma^2 \)

Pulse duration selection:
(monochromator bandwidth and amount of chirping define pulse duration)

Stabilize central frequency:
(shot-to-shot jitter in mean electron beam energy)
## Two-stage LCLS FEL Parameters:

**LCLS FEL Parameters:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation wavelength</td>
<td>1.5 Å</td>
</tr>
<tr>
<td>FEL parameter</td>
<td>$4.7 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>Undulator type</td>
<td>planar</td>
</tr>
<tr>
<td>Undulator period</td>
<td>3 cm</td>
</tr>
<tr>
<td>Peak magnetic field</td>
<td>1.32 T</td>
</tr>
<tr>
<td>Undulator strength parameter</td>
<td>3.71</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>120 Hz</td>
</tr>
</tbody>
</table>

**Electron Beam Parameters:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron energy</td>
<td>14.3 GeV</td>
</tr>
<tr>
<td>Norm. beam emittance</td>
<td>1.1 mm mrad</td>
</tr>
<tr>
<td>Average beta function</td>
<td>18 m</td>
</tr>
</tbody>
</table>

**Undulator 1:** ($L_1 = 43.20$ m)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak current</td>
<td>3.4 kA</td>
</tr>
<tr>
<td>Bunch duration, rms</td>
<td>120 fs</td>
</tr>
<tr>
<td>Uncorrelated energy spread, rms</td>
<td>0.006 %</td>
</tr>
<tr>
<td>Correlated energy chirp (FWHM)</td>
<td>0.5 %</td>
</tr>
</tbody>
</table>

**Undulator 2:** ($L_2 = 51.84$ m)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak current</td>
<td>4.0 kA</td>
</tr>
<tr>
<td>Bunch duration, rms</td>
<td>103 fs</td>
</tr>
<tr>
<td>Uncorrelated energy spread, rms</td>
<td>0.008 %</td>
</tr>
</tbody>
</table>
First Undulator:

\[ L_1 = 43.2 \text{ m} < L_{\text{sat}}^{\text{SASE}} \]

**Input Electron Beam Parameters:**
- Peak current: 3.4 kA
- Bunch duration, rms: 120 fs
- Energy spread, rms: 0.006 %
- Energy chirp (FWHM): 0.5 %

**Output Radiation Parameters:**
- Mean peak power: 13 MW
- Frequency chirp: 1 %
- FEL bandwidth: 2.7 \times 10^{-4}
- Rayleigh range: 40 m

**Require:**

\[ \langle P_{\text{out}}^{(1)} \rangle \ll P_{\text{sat}} \]

- Reduce damage to optical elements of monochromator.
- Energy spread of electron beam after the first undulator will satisfy

\[ \sigma_\gamma \approx \rho \sqrt{\frac{\langle P_{\text{out}}^{(1)} \rangle}{P_{\text{sat}}}} < \rho \]

Simulation results obtained using GENESIS 1.3
Monochromator: femtosecond radiation pulse generation

\[
\left( \frac{\Delta \lambda}{\lambda} \right)_{\text{chirp}} \equiv 10^{-2}
\]

\[
T_m = 41\%
\]

\[
\langle P_{\text{out}}^{(1)} \rangle T_m
\]

\[
L_{\text{FWHM}} \equiv 8.7 \text{ fs}
\]

\[
\left( \frac{\sigma_{\lambda}}{\lambda} \right)_{\text{rms}}^{\text{(mono)}} \equiv 1.3 \times 10^{-4}
\]
Monochromator:

Bandwidth selection by Bragg diffraction in crystals [e.g., Ge(111)]:

\[ \text{path delay} = \Delta L = 2d \tan \theta \]

Monochromator Parameters: Ge(111)

- Nominal photon energy: 8.3 keV
- Reflection angle: 0.24 rad
- Monochromator bandwidth, rms: \(1.3 \times 10^{-4}\)
- Power transmission (0.8/reflection): \(T_m = 41\%\)
- Tunability: 4.0 – 8.5 keV
- Photon beam path delay: 5 mm
Electron Beam Bypass:

Bypass Parameters:
- Total Length: 32.4 m
- $R_{56}$: 3.6 mm
- Path delay: 5.0 mm
- Maximum displacement: 20.5 cm
- Deflection angle: 1.68 deg
- Bend magnetic field: 0.4 T
- Bend magnet length: 3.5 m
- Quadrupole strength (max): 82 T/m
- Quadrupole length: 50 cm

Schematic of non-isochronous achromatic chicane for electron beam bypass:
Second Undulator:

Require:

\[ P_{\text{shot}} \ll \left\langle P_{\text{in}}^{(2)} \right\rangle = \left\langle P_{\text{out}}^{(1)} \right\rangle T_m T_{\text{diff}} \]

Radiation power from monochromator dominates over the shot noise, such that the FEL will amplify the input signal radiation (with bandwidth compared to SASE FEL bandwidth).

\[ L_2 = 51.84 < L_{\text{sat}}^{\text{SASE}} \]

\[ \left\langle P_{\text{out}}^{(2)} \right\rangle = P_{\text{sat}} \]

Simulation results obtained using GENESIS 1.3

Input Electron Beam Parameters:
- Peak current: 4.0 kA
- Bunch duration, rms: 103 fs
- Energy spread, rms: 0.008 %

Input Radiation Parameters:
- Mean peak power: 3.2 MW
- Pulse duration, FWHM: 8.7 fs
- Bandwidth, rms: 1.3\cdot 10^{-4}
- Intensity Fluctuations: 30 %
Shot-to-shot fluctuations:

Radiation Probability Distribution after Monochromator:

Negative Binomial Distribution

\[ p(P) = \frac{\Gamma(P + M)}{\Gamma(P + 1)\Gamma(M)} \left( 1 + \frac{M}{\langle P^{(2)}_{\text{in}} \rangle} \right)^{-P} \left( 1 + \frac{\langle P^{(2)}_{\text{in}} \rangle}{M} \right)^{-M} \]

Standard deviation of radiation power into second undulator:

\[ \sigma_P = \frac{1}{\sqrt{M}} \approx \sqrt{\frac{2\pi\sigma_c}{L_p}} \]

Dependence of output power on input power for FEL amplifier

Relative rms fluctuations of output radiation power

Shot-to-shot fluctuations of output radiation power are reduced by operating the FEL amplifier in the non-linear regime.
## Output Radiation Parameters for Two-Stage LCLS:

### Two-Stage FEL Output Radiation:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation wavelength</td>
<td>1.5 Å</td>
</tr>
<tr>
<td>Bandwidth, FWHM</td>
<td>$3.1 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>Pulse duration, FWHM</td>
<td>8.7 fs</td>
</tr>
<tr>
<td>Mean peak power</td>
<td>23 GW</td>
</tr>
<tr>
<td>Power fluctuations, rms</td>
<td>2 %</td>
</tr>
<tr>
<td>RMS spot size</td>
<td>31 μm</td>
</tr>
<tr>
<td>RMS angular divergence</td>
<td>0.5 rad</td>
</tr>
</tbody>
</table>

### Mean Peak Radiation Power:

![Graph showing mean peak radiation power vs. meters.](image)

Simulation results obtained using GENESIS 1.3
Monochromator: short pulse limit

Monochromator with smaller bandwidth slices out shorter pulse
\[ \delta t_{\text{out}} = \delta t_{\text{in}} \times \frac{\delta \omega_{\text{mono}}}{\delta \omega_{\text{chirp}}} \]

But uncertainty principle gives a limit
\[ \delta \omega_{\text{mono}} \times \delta t_{\text{out}} \leq \frac{1}{2} \]

Note that if the uncertainty principle dominates, then the output pulse has complete longitudinal coherence.

For LCLS at 8 keV with 1% chirp, the minimum pulse length is about 3.5 fs fwhm, using a monochromator resolution of 3.3x10^{-5} rms.

Some practical monochromator options:

<table>
<thead>
<tr>
<th>Crystal reflection</th>
<th>rms resolution</th>
<th>Output pulse fwhm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ge(111)</td>
<td>14x10^{-5}</td>
<td>9 fs</td>
</tr>
<tr>
<td>Si(111)</td>
<td>5.7x10^{-5}</td>
<td>4.1 fs</td>
</tr>
<tr>
<td>Si(220)</td>
<td>2.5x10^{-5}</td>
<td>4.1 fs</td>
</tr>
</tbody>
</table>
Conclusions

The Two-Stage Chirped-Beam SASE-FEL offers:

- An attractive way to produce high intensity X-ray pulses in the 10 to 20 fs range
- Improved stability of the central frequency
- Reduced load on optical elements
- It can be built as an upgrade to present LCLS design